Exhibit A

RF Systems, Components, and Circuits Handbook

Ferril Losee

Artech House
Boston • London

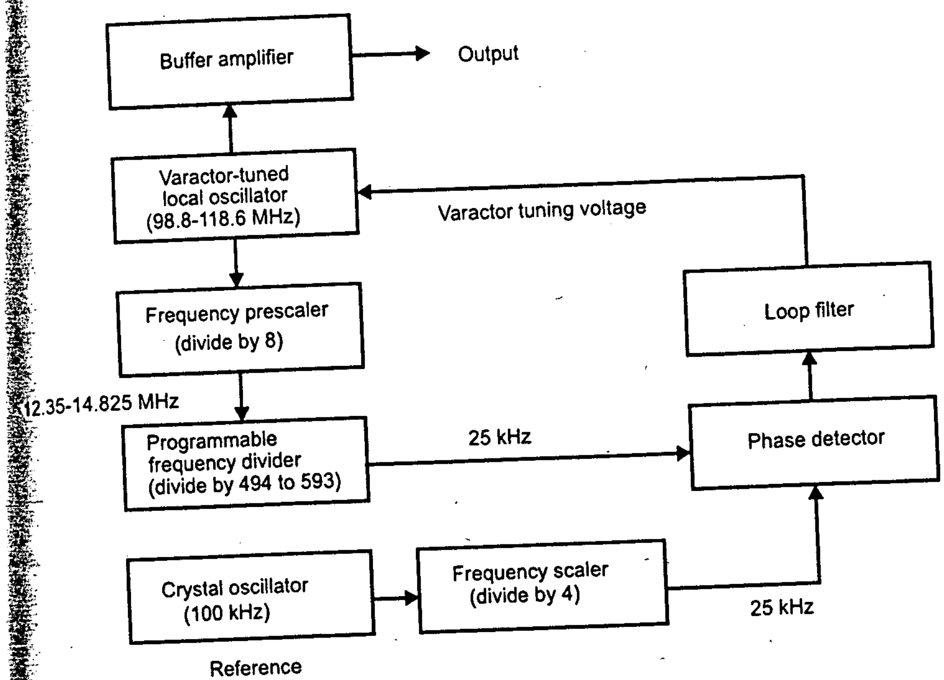

Figure 6.12 An indirect frequency synthesizer. (*After:* [6].)

the tuning circuitry is easier to construct and simpler. Also, YIG-tuned oscillators can suffer from tuning hysteresis.

It is common practice to use a buffer amplifier between the oscillator or frequency synthesizer that feeds the carrier frequency to the modulator circuit. Doing so provides isolation and a good impedance match between the VCO and the equipment to which it is connected. The use of a buffer amplifier also increases gain to provide sufficient power out for a mixer it may be driving. An alternative is to use an isolator (discussed in Chapter 11).

6.3 FREQUENCY MULTIPLIERS

The nonlinearity inherent in any semiconductor diode or transistor can be used to multiply frequency. The most popular diode frequency multipliers use either varactor diodes or step-recovery diodes. Frequency multipliers of this type are discussed in this section. Some of the information presented here is adapted from [5,7].

6.3.1 Varactor Diode Frequency Multipliers

Figure 6.13 shows a varactor-diode frequency tripler. Input and output impedance-matching circuits are used with this circuit. The input and output ports are coupled to the diode through series-tuned circuits, causing the input current and the output current and voltage to be essentially sinusoidal.

The varactor diode is a nonlinear voltage-variable capacitor. One or more so-called idler circuits are used with the circuit. These series-tuned circuits are placed in parallel with the diode and are resonant at harmonic frequencies other than the desired output frequency. Idler circuits are in practice empirically selected and adjusted to improve efficiency. They are resonant at other harmonics, presenting an impedance to reflect unwanted harmonic energy back to the input.

Hyperabrupt snap-off varactor diodes multiply by high factors with better efficiency than ordinary varactor diodes, so they are used wherever possible. GaAs varactors often are used at the higher frequencies. A varactor multiplier of this type can have an efficiency for a 60-GHz doubler of greater than 50%.

The maximum output power for the varactor diode multipliers ranges from more than 10W at 2 GHz to about 25 mW at 100 GHz. Tripler efficiencies range from 70% at 2 GHz to about 40% at 36 GHz. One of the current applications for multiplier chains is to provide a low-power signal to phase-lock a Gunn or IMPATT oscillator.

6.3.2 Step-Recovery Diode Frequency Multipliers

A step-recovery diode is a silicon or GaAs p-n junction diode with construction similar to that of a varactor diode. It stores charge when conducting in the forward direction. When reverse bias is applied, the diode very briefly discharges the stored energy in the form of a sharp pulse that is rich in harmonics. The duration of the pulse typically is only 100 to 1,000 picoseconds (ps) (1 ps = 10^{-12} sec), depending on diode design.

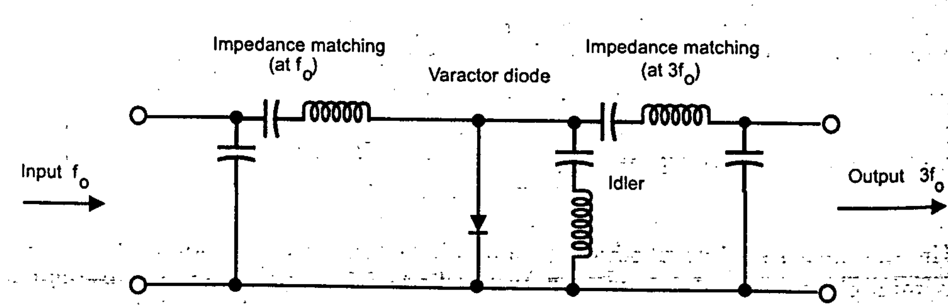

Figure 6.13 Varactor diode tripler circuit. (*After:* [5].)

Step-recovery diodes are frequently use is essentially the same as that used for the that an inductor is used in series with the ste when the charge is completely drained from t to a nonconducting state. This abrupt chan tor, which has stored energy, to generate a flat frequency spectrum. Thus, the circuit i desired harmonic frequency component is t circuit and appropriate idler networks.

Figure 6.14 shows a typical multiplie varactors. The first stage is a transistor cry with 35W output power at 160 MHz. That i a tuned circuit that is tuned to the tenth l output power of this stage is 3.5W, and the stage is a step-recovery diode with a tuned c of 1.6 GHz or 8.0 GHz. The output pow frequency is 8 GHz. The last two stages of of those stages is a tripler with an output fr of 1,100 mW. The last stage is a doubler v an output power of 275 mW.

Frequency multipliers at microwave f ial line, or waveguide. Step-recovery diod about 20 GHz, whereas varactors can be

Step-recovery diodes are available f 10W at 2 GHz, and 1W at 10 GHz. Mult available. Efficiency can be in excess of 80 The efficiency drops to about 15% for a 5 of 12 GHz.

6.3.3 Transistor Multipliers

Transistor multipliers also are frequentl exhibit less loss than varactors or SRDs circuit is similar to that of a small-signal the desired harmonic of the input sign.

A class A doubler can be made characteristic. Again, the circuit can b the output circuit tuned to the secon efficiency for this type of frequency mu

Class C frequency multipliers are p ples and procedures generally are the output circuit is tuned to the desired l

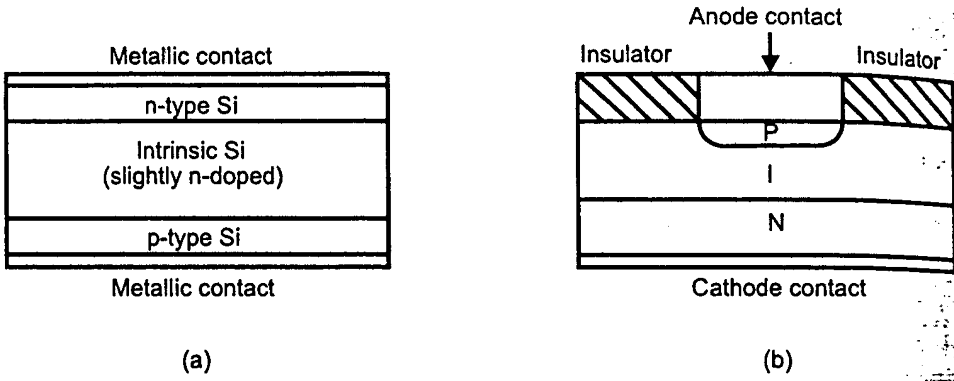

Figure 17.2 PIN diode: (a) schematic diagram and (b) planar PIN diode.

The PIN diode is used for microwave power switching, attenuating, limiting, and modulation. At microwave frequencies, the PIN diode acts as a variable resistance. The simplified equivalent circuits and the resistance variation with reverse and forward bias are shown in Figure 17.3(a,b). With reverse (negative) bias, the resistance to microwave energy typically is about 5,000–10,000Ω. When the diode is forward biased, the positive-bias resistance to microwave energy is typically 1–10Ω. If the PIN diode is placed across a waveguide, a 50Ω coaxial line or other transmission medium, it does not significantly load the line when negatively biased. When positively biased, however, it presents a near short circuit across the line and thus produces reflections on the line.

Figure 17.3(c) is a schematic diagram of a series-mounted PIN diode switch for a coaxial or microstrip line. The dc bias is fed into the diode using an RF choke, and the signal is injected using a coupling capacitor. The output is across an RF choke to ground.

Figure 17.3(d) is a schematic diagram for a shunt-mounted PIN diode switch for a coax line. Again, the dc bias is fed in to the diode using an RF choke, and the signal is fed in using a coupling capacitor. In this case, no output choke is used, and the PIN diode is connected directly to ground. The output is fed out using a coupling capacitor.

PIN diodes can be used in parallel or series, as desired. Individual diodes can handle up to about 200 kW peak or 200W average. Several diodes in parallel can handle as much a 1 MW peak. Switching times are in the range of 1–40 ns, depending on the power levels used.

17.6 VARACTOR DIODES

Almost every semiconductor diode has a junction capacitance that varies with the applied reverse bias. If the diode is manufactured to have suitable microwave

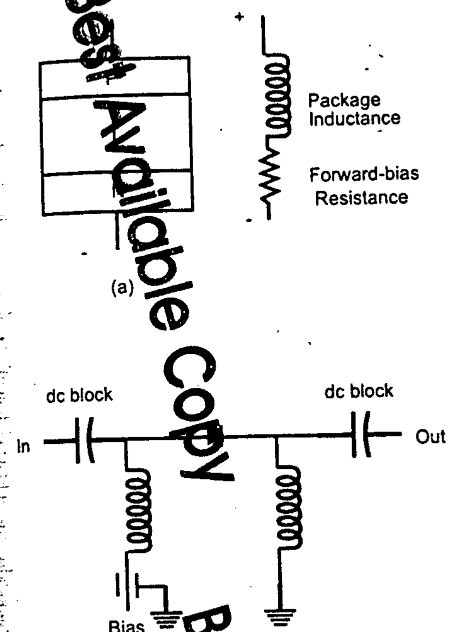

Figure 17.3 PIN diode simplified equivalent circu
(b) reverse bias condition; (c) series

characteristics, it is called a varactor dio
GaAs has the advantage of higher m
shows the characteristics of varactor d
characteristics and the junction capacit
voltage region of interest for a varactor
breakdown point and zero volts. For ty
is about [illegible]F and the maximum capac
Varactors find application as volta
tion and oscillator tuning. They also
snap-off varactor diodes multiply by hig
varactor diodes, they are used where p
higher frequencies. A varactor multipl
60-GHz doublers of greater than 50%.
The maximum output power for
more than 10W at 2 GHz to about 25
from 70% at 2 GHz to about 40% at 3
including idlers to reflect fundament
input. Otherwise, [illegible]% efficiency is m

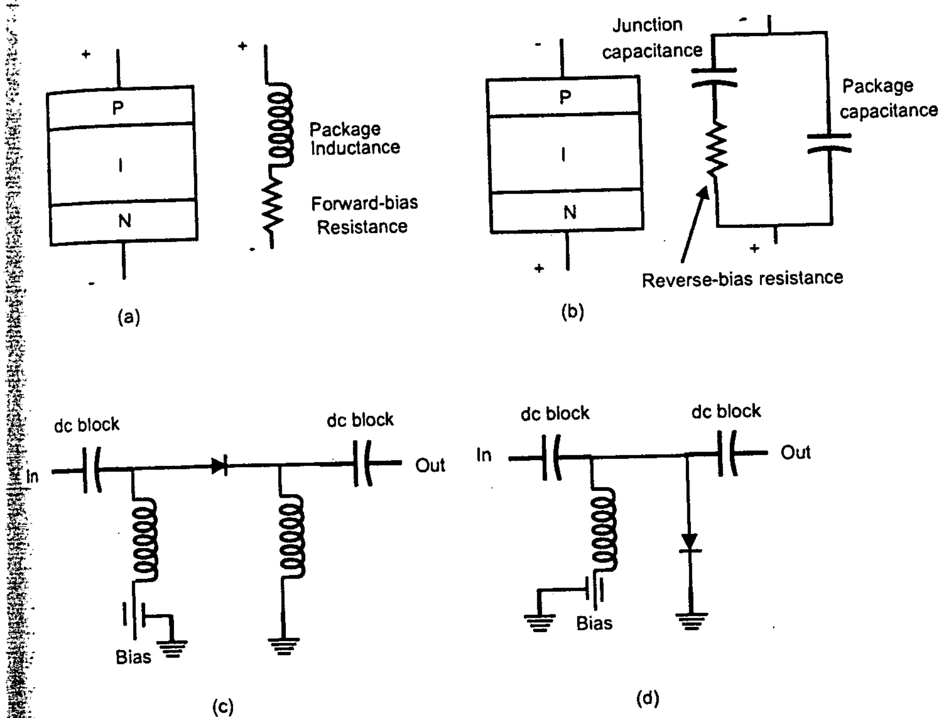

Figure 17.3 PIN diode simplified equivalent circuits and example switches: (a) forward bias condition; (b) reverse bias condition; (c) series-mounted switch; and (d) shunt-mounted switch.

characteristics, it is called a varactor diode. Varactor diodes are made of Si or GaAs. GaAs has the advantage of higher maximum operating frequency. Figure 17.4 shows the characteristics of varactor diodes, including the current versus voltage characteristics and the junction capacitance versus voltage characteristics. The bias voltage region of interest for a varactor diode is between just above the avalanche breakdown point and zero volts. For typical Si varactors, the minimum capacitance is about 1 pF and the maximum capacitance is about 25 pF.

Varactors find application as voltage-variable capacitors for frequency modulation and oscillator tuning. They also are used in frequency multipliers. Because snap-off varactor diodes multiply by high factors with better efficiency than ordinary varactor diodes, they are used where possible. GaAs varactors often are used at the higher frequencies. A varactor multiplier of this type can have an efficiency for a 60-GHz doubler of greater than 50%.

The maximum output power for the varactor diode multipliers ranges from more than 10W at 2 GHz to about 25 mW at 100 GHz. Tripler efficiencies range from 70% at 2 GHz to about 40% at 36 GHz; however, that is with proper design, including idlers to reflect fundamental and second harmonic power back to the input. Otherwise, 33% efficiency is more typical.

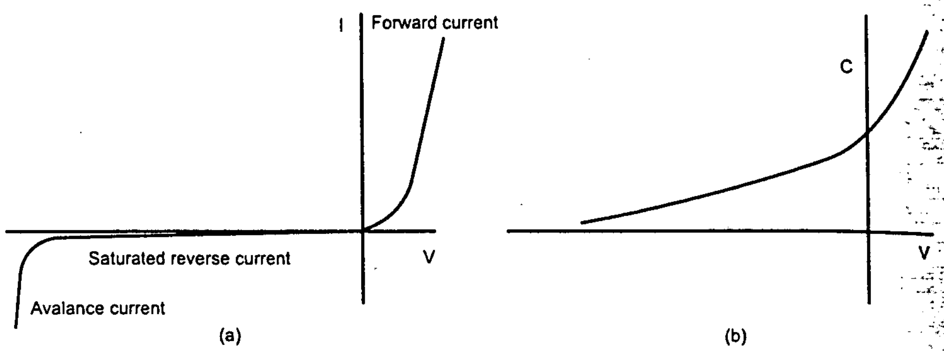

Figure 17.4 Varactor diode characteristics: (a) current versus voltage and (b) capacitance versus voltage. (*After:* [2].)

One of the current applications for multiplier chains is to provide a low-power signal to phase-lock a Gunn or IMPATT diode oscillator. (These devices are discussed later.)

17.7 STEP-RECOVERY DIODES

A step-recovery diode is a Si or GaAs p-n junction diode with construction similar to that of a varactor diode. It stores charge when conducting in the forward direction. When reverse bias is applied, the diode briefly discharges the stored energy in the form of a sharp pulse, an impulse, that is rich in harmonics. The duration of the pulse typically is only 100 to 1,000 ps, depending on diode design.

Step-recovery diodes are not available for frequencies above about 20 GHz, whereas varactors can be used well above 100 GHz. Step-recovery diodes are available for powers in excess of 50W at 300 MHz, 10W at 2 GHz, and 1W at 10 GHz. Multiplication ratios up to 12 commonly are available. Efficiency can be in excess of 50% for triplers at frequencies up to 1 GHz. The efficiency drops to about 15% for a times-5 multiplier with an output frequency of 12 GHz.

17.8 MICROWAVE TUNNEL DIODES AND CIRCUITS

Figure 17.5 shows the voltage-current characteristics for a Ge junction tunnel diode. This diode differs from the ordinary junction diode in that the semiconductor material is heavily doped, perhaps 1,000 times that of an ordinary rectifier diode. That permits a depletion layer so thin that tunneling can occur easily.

In the voltage region from A to B, there is a region of negative resistance. That means that this device can be used as an oscillator. The tunnel diode oscillator found use early after its development, but it no longer is used extensively because other negative-resistance semiconductor devices now provide higher output power.

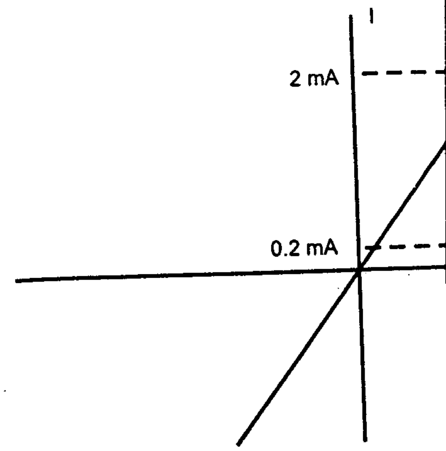

Figure 17.5 Tunnel diode voltage-current charact

The tunnel diode also can be use
a circulator. A circuit of this type is show
(TDA) is a low-noise system. Reasons
resistance device, and the operating c
be fairly broadband systems. They are
microwave frequencies with upper limi

17.9 MICROWAVE GUNN DIODES A

Figure 17.7 shows an epitaxial GaAs G
by such a device if the voltage gradient
3,300 V/cm.

Oscillations then occur if the sl
Proper doping profile is also required

The Gunn effect is a bulk prope
on either junction or contact propert
associated only with electrons and no
which the Gunn effect works. In this m
energy band higher in energy than th
forbidden energy gap is small. In th
electrons acquire enough energy to
which they are much less mobile. Th
of voltage rise. This voltage region
Eventually with increasing voltage, t
electrons from the higher energy, lo
with voltage once again.